Chapter 2
Sampling Requirements

2-1. Introduction

The principal objective of a subsurface investigation is to define the geotechnical engineering characteristics, including permeability, compressibility, and shear strength, of each identifiable soil or rock stratum within a limited areal extent and depth, depending upon the size of the proposed structure. A secondary objective may be to identify and correlate the geology and stratigraphy of like materials. The investigation should be planned within this context to account for appropriate foundation and earthworks design, temporary works design, environmental effects, existing construction, remedial works, and safety checks. These criteria should also be considered for the evaluation of the feasibility and suitability of a particular site.

To fulfill the objectives of the site investigation, the study may be subdivided into five phases: preliminary studies, field subsurface investigation, laboratory testing, reporting, and proposals. The field subsurface investigation is the only phase which falls within the scope of this manual. Preliminary studies, which include the review of published literature, maps, and photographs, and field reconnaissance, are described in EM 1110-1-1804 and other references such as Bell (1987a); Clayton, Simons, and Matthews (1982); Dowding (1979); Mathewson (1981); and Winterkorn and Fang (1975). The laboratory testing phase is discussed in EM 1110-2-1906. A comprehensive list of references cited in this manual are presented in Appendix A. Final reports and proposals are addressed elsewhere.

The comprehensive field subsurface investigation can be executed by using data obtained by remote sensing techniques, such as geophysical methods described in EM 1110-1-1802; by indirect observations which include in situ tests; such as pressuremeter, cone penetration, and plate bearing tests; and by direct observations which include cores, test pits and trenches, and shafts and adits, as well as field reconnaissance. Although the most economical and thorough subsurface investigation can be conducted by integrating all of these technologies, only the direct observation techniques, i.e., drilling and sampling methods, are discussed herein.

Direct observation of subsurface conditions can be obtained by examination of formations through the use of accessible excavations, such as shafts, tunnels, test pits, or trenches, or by drilling and sampling to obtain cores or cuttings. Table 2-1 lists direct methods of subsurface investigations. Test pits and trenches probably offer the best method for observing in situ conditions and obtaining high quality undisturbed samples. A two- or three-dimensional profile of the subsurface strata can be obtained by examination of the walls and floor of the excavation. However, test pits and trenches are generally not economically feasible at depths, especially below the groundwater table.

Core drilling is a fairly economical method for obtaining representative samples at depth. Disturbed samples can be obtained by augering, percussion, and wash boring methods; undisturbed samples can be obtained by employing undisturbed sampling methods which include push tube samples and rotary core barrel samples. The potential for predicting in situ behavior based upon disturbed samples is limited because the effects of sampling disturbance are not totally clear. As compared to the profile obtained from test pits and trenches, only a one-dimensional profile can be obtained from cores and cuttings from boreholes.

Disturbed samples from stockpiles and storage bins can be obtained from hand-excavated trenches or by using power equipment. The sampling methods and procedures are similar to those methods and procedures which are used for obtaining samples from in situ formations. When samples are obtained from stockpiles and storage bins, special care is needed to ensure that the samples are representative, as segregation may occur as a result of the material handling procedures which are employed, i.e., coarser and finer particles tend to segregate as cohesionless soils are end dumped from a conveyor belt.

2-2. Sample Quality

Hvorslev (1949) defined the quality of samples as representative or nonrepresentative. He defined nonrepresentative samples as mixtures of soil and rock from different layers. He further suggested that nonrepresentative samples are normally not useful in site investigations and emphasized that serious errors of interpretation of the soil profile could result due to the mixing of soil cuttings. Nonrepresentative samples are produced by wash boring and bailing and by some types of augering. Hvorslev defined representative samples as those materials which may have been remolded or the moisture content may have changed, although the materials were not chemically altered or contaminated by particles from other layers. Representative samples may be obtained by a variety of techniques, depending upon the quality of sample desired.

Disturbed samples can be obtained by augers, sampling spoons, and thick- and thin-walled sampling tubes. Disturbed samples are primarily used for moisture content, Atterberg limits, specific gravity, sieve analysis or grain-size distribution, and compaction characteristics. Strength and deformation tests may be conducted on reconstituted (remolded) specimens of the disturbed materials. Tests on remolded samples are used to predict the behavior of compacted embankments and backfills. Undisturbed samples have been subjected to relatively little disturbance and may be obtained from borings using push-type or rotary-core samplers. High-quality undisturbed samples may be obtained by hand trimming block samples from test pits and trenches. Undisturbed samples are useful for strength, compressibility, and permeability tests of the foundation materials.

2-3. Parameters Which Affect Sample Disturbance

Hvorslev (1949) defined several critical factors which could cause disturbance of the soil during sampling operations. These parameters include area or kerf ratio, friction between the sampling tube and the soil, the length-to-diameter ratio of the sample, sampler driving techniques, stress relief, and failure to recover a sample.

a. Area ratio. Hvorslev stated that the area ratio, C_a, may be the most significant single factor which could influence the quality of the undisturbed sample. He defined the area ratio as

$$C_a = \frac{D_w^2 - D_e^2}{D_e^2} \tag{2-1}$$

where

D_w = external diameter of the cutting shoe

D_e = internal diameter of the cutting shoe

The internal and external diameter of the cutting shoe are illustrated conceptually in Figure 2-1. Permissible area ratios depend upon the soil type, its strength and sensitivity, and the purpose of the sampling operations. Hvorslev suggested that area ratios should be kept to a minimum value, preferably less than 10 to 15 percent. However, small area ratios result in fragile sample tubes which may bend or buckle during sampling operations. To permit the use of larger area ratio tubes, the International Society for Soil Mechanics and Foundations Engineering (1966) approved the use of larger area ratios provided that cutting edge taper angles were changed. The Committee suggested that as area ratios were increased from 5 to 20 percent, the edge taper angles should be decreased from 15 to 9 degrees (deg).

b. Inside clearance ratio. Friction between the soil sample and inside wall of the sample tube may be reduced by cutting the diameter of the sample slightly smaller than the inside diameter of the sample tube. The inside clearance ratio, or swage, C_i, is defined as

$$C_i = \frac{D_s - D_e}{D_e} \tag{2-2}$$

where D_s is the inside diameter of sampling tube. The inside diameter of sampling tube and the internal diameter of the cutting shoe are illustrated conceptually in Figure 2-1. Hvorslev suggested that ratios of 0 to l percent may be used for very short samples, values of 0.5 to 3 percent could be used for medium length samples, and larger ratios may be needed for longer samples. For most soils, an inside clearance ratio of 0.75 to 1.5 percent is suggested for samples with a length-to-diameter ratio of 6 to 8, i.e., medium length samples. However, the clearance ratio should be adjusted as required by the character of the soil.

c. Outside clearance ratio. The outside wall friction may also influence the quality of the soil sample. Severe wall friction may be transmitted to the soil lying beneath the bottom of the sampler, and a bearing capacity failure could result. If a bearing capacity failure occurred during the sampling operations, the material entering the tube could be rendered useless even for visual examination. The practical range for outside clearance ratios should be less than 2 to 3 percent for cohesive soils and zero for cohesionless soils, although these values may require adjustment for the character of the soil. The outside clearance ratio, C_o, is defined as

$$C_o = \frac{D_w - D_t}{D_t} \tag{2-3}$$

where D_t is the outside diameter of sampling tube. The outside diameter of sampling tube and the external diameter of the cutting shoe are illustrated conceptually in Figure 2-1.

d. Length-to-diameter ratio. The maximum length for an undisturbed sample which can be obtained in a single sampling operation is dependent upon the type of soil, the sampler, the rate and uniformity of penetration, the inside clearance ratio, and the depth below the ground surface. Suggested ratios of length to diameter of the sample should be limited to 5 to 10 for cohesionless soils and 10 to 20 for cohesive soils, although these ratios may vary as a result of the variables encountered and the type of sampler employed. The diameter of the sample should be selected based upon the type of soil, the laboratory requirements, and practical considerations, such as availability of equipment.

e. Advancing the sample tube. The method of advancing the sample tube affects the disturbance of the soil. Driving the sample tube by hammering causes the greatest amount of disturbance. Pushing the sampling tube with a fast, continuous, uniform motion is recommended as a suitable method of advancing the sample tube in most soils.

f. Stress relief. Stress relief can result in base heave, caving, and piping in the borehole. The borehole may be stabilized by using water, drilling mud, or casing. Water is the least effective method. It works by reducing the effective stresses along the sides and bottom of the borehole and decreasing the groundwater flow into the borehole. Although this method may not be successful for many soils, it may work well in soft cohesive alluvial deposits. Drilling mud, which usually consists of bentonite mixed with water in a ratio by weight of approximately 1:15 to 1:20, has several advantages over water. The unit weight of drilling mud is slightly higher than the unit weight of water and thus reduces the effective stresses within the subsurface formations. The drilling mud forms a filter or wall cake which reduces seepage as well as the rate and amount of swelling for water sensitive deposits. Disadvantages include increased costs and the need for disposal of the drilling mud after the drilling operations have been completed. Steel casing can also be used to prevent wall collapse but may disturb the soil formation during its placement. The use of casing may be limited by economic considerations.

g. Sample recovery. Poor sample recovery may be the most serious result of sample disturbance and may be dependent on a number of factors which include:

(1) Increased pressure at the top of the sample due to improper venting of the sample tube during sampling operations. The pressure tends to force the soil from the tube as the sample is extracted from the boring.

(2) Suction below the sample tube results as the tube is pulled from the soil deposit. Several techniques, including the use of a piston sampler which opposes with a vacuum or suction as the sample tends to slide from the tube, enhance the length and degree of sample recovery.

(3) The tensile strength of the soil must be overcome to separate the soil sample from the soil deposit. This separation may be accomplished by rotating the sampling tube one or two revolutions to shear the sample at the base of the cutting shoe. Other techniques are: (a) allowing a short rest period after sampling to permit the soil to swell and increase adhesion with the wall of the sample tube, (b) slight overdriving which increases sample disturbance but simultaneously increases adhesion between the sample and sample tube wall, and (c) the use of core catchers. It should be noted that core catchers tend to increase the disturbance around the edge of the sample. The area ratio of the cutting shoe may also have to be increased to accommodate the core catcher.

(4) Remolding of soils adjacent to the sampler walls may reduce the chances of recovery, especially for sensitive soils. A small area ratio and cutting edge with increased swage taper may be essential to obtain quality samples of many soils.

Hvorslev (1949) attempted to conduct a qualitative assessment of sampling disturbance by the use of a ratio of the length of the recovered sample to the length of the sample drive or push. He called this quantity “recovery ratio.” Although the recovery ratio is probably an index of sample quality, many variables affected the ratio. Unfortunately, Hvorslev was unable to isolate the criteria required to assess sample disturbance using the recovery ratio concept.

Disturbance which occurs after sampling may result from a change of water content, moisture migration within the sample, the penetration of voids by wax used to seal the sample, vibrations during the transport of samples, freezing of silt or clay samples, chemical reaction between the soil sample and the tube, or disturbance caused by extruding the sample from the tube.

It is important that practices are adopted to obtain the highest quality sample at the least cost. Undisturbed sampling should be conducted in a manner to minimize: (a) changes of void ratio and water content, (b) mechanical disturbance of the soil structure, and (c) changes of stress conditions. Efforts should also be undertaken to eliminate other causes of disturbance, such as chemical changes, caused by prolonged storage in metal containers. A summary of the principal causes of soil disturbance is presented in Table 2-2.

2-4. Selection of Sampling Apparatus to Obtain Undisturbed Samples

Although the least disturbed samples are probably obtained by the hand trimming method in test pits and trenches using the advanced trimming technique, the depth at which samples can be obtained economically usually limits the use of test pits for sampling operations. Consequently, other sampling techniques must be employed. Two basic types of sampling apparatus which have been developed are (i) push-tube samplers and (ii) core barrel samplers. Additional details describing equipment and procedures for undisturbed sampling operations are discussed in Chapters 5 and 6, respectively.

a. Push-tube samplers. Push-tube samplers are pushed into the soil without rotation. The volume of soil which is displaced by the sampling tube is compacted or compressed into the surrounding soils. Thin-walled push-tube samplers can be subdivided into two broad groups: open-tube samplers and piston samplers. Open-tube samplers consist of open tubes which admit soil as soon as they are brought in contact with it. Many open samplers have a ball check valve located in the sampler head which connects the sample tube to the drill string. The purpose of the check valve is to help retain the sample in the sampling tube during extraction. Piston samplers have a piston located within the sampler tube. The piston helps to keep drilling fluid and soil cuttings out of the sampling tube as the sampler is lowered into the borehole. It also helps to retain the sample in the sampling tube.

(1) *Open-tube samplers*. Open-tube samplers for undisturbed sampling are thin-walled tubes. The thin-walled open-tube push sampler consists of a Shelby tube affixed to the sampler head with Allen head screws as suggested by ASTM D 1587-74 (ASTM 1993). Most tubes are drawn to provide a suitable inside clearance. The cutting edge of the sampling tubes is normally sharpened. Thin-walled sample tubes may be easily damaged by buckling, blunting, or tearing of the cutting edge as they are advanced into stiff or stony soils. Open-tube samplers have advantages due to cheapness, ruggedness, and simplicity of operation. The disadvantages include the potential for obtaining nonrepresentative samples because of improper cleaning of the borehole or collapse of the sides of the borehole. An increase of pressure above the sample during sampling operations and a decrease of pressure caused by sample retention during the withdrawal of the sampling tube from the borehole may also influence the quality of the sample. Hence, open-tube samplers are generally not recommended for undisturbed sampling operations.

(2) *Piston samplers*. Pistons have been incorporated into sampler designs to prevent soil from entering the sampling tube before the sampling depth is attained and to reduce sample loss during withdrawal of the sampling tube and sample. The vacuum which is formed by the movement of the piston away from the end of the sampling tube during sampling operations tends to increase the length to diameter ratio. The advantages of the piston samplers include: debris is prevented from entering the sampling tube prior to sampling; excess soil is prevented from entering the sampling tube during sampling; and sample quality and recovery is increased. Hvorslev (1949) stated that the fixed-piston sampler “has more advantages and comes closer to fulfilling the requirements for an all-purpose sampler than any other type.” The principal disadvantages of piston samplers include increased complexity and cost.

Three general types of piston samplers are free-piston samplers, fixed-piston samplers, and retractable-piston samplers.

(a) Free-piston samplers have an internal piston which may be clamped during insertion or withdrawal of the sampling tube. During actual sampling operations, the piston is free to move with respect to the ground level and sample tube. Free-piston samplers have overcome many of the shortcomings of open-tube samplers while remaining easy to use. Principal advantages include: the sample tube can be pushed through debris to the desired sampling depth and the piston creates a vacuum on the top of the sample which assists in obtaining increased sample recovery.

(b) To obtain a sample with a fixed-piston sampler, the sampling apparatus is lowered to the desired level of sampling with the piston fixed at the bottom of the sampling tube. The piston is then freed from the sampler head, although it remains fixed relative to the ground surface, i.e., it can be affixed to the drill rig. The sample is obtained, and the piston is again clamped relative to the sampler head prior to the removal of the sample and sampling tube from the borehole. The Osterberg sampler and the Hvorslev sampler are fixed-piston samplers commonly used by the Corps of Engineers.

(c) The retractable-piston sampler uses the piston to prevent unwanted debris from entering the sample tube while the sampler is lowered to the desired sampling depth. Prior to the sampling operation, the piston is retracted to the top of the tube. However, this operation may cause soil to flow upward into the tube; if this occurs, the quality of the sample is suspect. The retractable piston sampler is not recommended for undisturbed sampling operations.

(d) A modified form of the fixed-piston sampler is the foil or stockinette sampler. The principle of operation is similar to the fixed-piston sampler. As the sample is obtained, the piston retracts from the sampler head, and a sliding liner, which is attached to the piston, unrolls from its housing located within the sampler head. The foil or stockinette sampler was designed to obtain samples with an increased length-to-diameter ratio by reducing friction between the sample and the wall of the sampling tube. Long samples can provide a more comprehensive understanding of a complex soil mass, such as varved clay. This type of sampler has also been used to obtain samples of soft clay and peat. The principal disadvantages of the foil or stockinette sampler include large operating expenses and increased potential of sample disturbance due to the larger area ratio of the cutting shoe. Examples of the sampler included the Swedish foil sampler and the Delft stocking sampler.

b. Core barrel samplers. Rotary core-barrel samplers were originally designed for sampling rock, although a variety of rotary samplers have been developed to sample materials from hard soils to soft rock. The principle of operation consists of rotating a cutting bit and applying a downward force from the ground surface with a drill rig. As the cutting edge is advanced, the sample tube is pushed over the sample. Drilling fluid, such as air or drilling mud, is used to cool the drill bit and remove the cuttings from the face of the bit.

Rotary core-barrel samplers have evolved from a single-tube sampler to double- and triple-tube samplers. The rotation of the core barrel of the single-tube sampler during the coring process presented a high potential for shearing the sample along planes of weakness. The design of the single-tube core barrel also exposed the core to erosion or degradation by the drilling fluid which was passed along its entire length. The double- and triple-tube core barrels were designed to minimize these problems. The double-tube core barrel sampler consists of an inner stationary tube and an outer tube which attaches the cutting bit to the drill rods. Drilling fluid is pumped through the drill rods and between the inner and outer barrels before being discharged through ports inside the cutting face of the bit. A modification of this technique is to discharge the drilling fluid through ports located on the face of the bit, i.e., bottom discharge bit. A spring catcher is frequently used to prevent loss of the core during the extraction process. The triple-tube core barrel consists of a double-tube core barrel which has been modified to accept a sample liner. The liner reduces the potential damage to the core as the sample is extracted from the inner tube. The liner also serves as a container to ship the core.

Core barrel samplers have a larger area ratio and inside clearance ratio than are generally accepted for push-tube samplers. The larger area ratio may be considered advantageous as it decreases the stress at the cutting bit during the drilling operations. However, the larger inside clearance ratio may not provide adequate support to the sample. During the drilling operations, the sample may be damaged by vibrations of the rotating core barrel. Another disadvantage is that although the inner core barrel may protect the core from erosion by the drilling fluid, water sensitive formations may be continuously in contact with the drilling fluid.

Two principal types of double- or triple-tube core barrel samplers include the Denison sampler and the Pitcher sampler.

(1) The Denison core barrel sampler consists of an inner liner, an inner barrel with an attached cutting edge, and an outer rotating barrel with attached cutting teeth. The protrusion of the inner barrel must be adjusted in advance of the drilling operations for the anticipated stiffness of the soil to be sampled. It can precede the cutting teeth for soft soils or can be flush with the cutting teeth for stiffer soils. The principal disadvantage of this type of sampler is that the protrusion of the inner tube must be selected in advance of the drilling operations. To overcome this problem, core barrel samplers with a spring-mounted inner barrel such as the Pitcher sampler, were developed.

(2) The Pitcher sampler consists of an inner barrel which is a thin-walled sample tube with a cutting edge. The tube is affixed to an inner sampler head. The outer rotating barrel has a cutting bit attached. After the sampler has been lowered into the borehole but before it has been seated on the soil, debris can be flushed from the sample tube by drilling fluid which is passed down the drill rods through the inner barrel. Once the inner tube is seated, drilling fluid is passed between the inner and outer tubes. A spring-loaded inner head assembly governs the

lead of the inner tube cutting edge with respect to the cutting bit. For softer formations, the cutting edge of the sample tube precedes the cutting bit. For stiffer soils, the cutting edge of the tube may be flush with the cutting bit. Although it has been observed in practice that alternating soil and rock layers may frequently damage the rather light sampling tube, this sampler may be used in formations of variable hardness where the push-tube sampler cannot penetrate the formation and the rotary core-barrel sampler does not protect the sample from erosion by the drilling fluid.

c. Sand samplers. Obtaining high-quality undisturbed samples of sand has been rather elusive. Hvorslev (1949) suggested several methods including the use of thin-walled fixed-piston samplers in mudded holes, open-tube samplers using compressed air, in situ freezing, and impregnation.

(1) The U.S. Army Engineer Waterways Experiment Station (1952) and Marcuson and Franklin (1979) reported studies using the thin-walled fixed-piston sampler. Pre- and post-sampling densities were compared. Generally, loose samples were denser and dense samples were looser.

(2) Bishop (1948) developed a sampler for sand. A differential pressure was employed to enhance the capability of retaining the sample in the sampling tube.

(3) Torrey, Dunbar, and Peterson (1988) reported an investigation of point bar deposits along the Mississippi River. The Osterberg fixed-piston sampler was used to obtain samples of fine sand below the water table. Although data were not available regarding the degree of disturbance, it was judged that high-quality samples were obtained based upon the comparison of all test results, including in situ tests, nuclear density tests, the examination of x-ray records for all undisturbed samples, laboratory tests, and data from previous potamology studies.

(4) Seed et al. (1982) reported an investigation of the effects of sampling disturbance on the cyclic strength characteristics of sands. They determined that the Hvorslev fixed-piston sampler caused density changes, whereas the advanced trimming and block sampling techniques caused little change in density, although some disturbance due to stress relief was reported.

(5) Singh, Seed, and Chan (1982) reported a laboratory study of techniques for obtaining undisturbed samples of sands. Unidirectional freezing with no impedance of drainage was followed by rotary core barrel sampling. Experimental data demonstrated that the freezing method could be used to obtain laboratory samples which maintained the in situ characteristics, including applied stress conditions.

(6) Schneider, Chameau, and Leonards (1989) reported a study to assess impregnation as a method for stabilizing cohesionless soils prior to conducting undisturbed sampling operations. They suggested that the impregnating material should readily penetrate the soil and must be easily and effectively removed at a later date. They also reported that impregnation of soil was fairly expensive and rather difficult to execute. Because of these considerations and limitations, Schneider, Chameau, and Leonards stated that chemical impregnation of soil has been generally limited to the laboratory environment, although they concluded that the technology could be readily applied to the field environment.

Although the technology is somewhat limited, data are available which indicate that high-quality undisturbed samples of sand can be obtained. However, the sampling techniques must be tailored to the characteristics of the formation and the requirements of the investigation. Furthermore, the allowable degree of disturbance to the “undisturbed” samples must be considered.

The highest quality undisturbed samples of medium to fine sands can be obtained by hand trimming or in situ freezing and core drilling. For shallow depths above the groundwater table, high quality samples can be obtained by hand trimming methods using the cylinder with advanced trimming technique. Below the groundwater table, in situ freezing with core drilling is a method which can be used to obtain high-quality samples. Another method which yields good quality samples of sand below the water table is the use of the fixed-piston sampler in a mudded borehole. For dry formations, impregnation of the material to be sampled may be the most suitable method for obtaining undisturbed samples. For coarser sands and gravelly soils, methods which are similar to the methods for sampling medium to fine sands can be used. It is suggested that the minimum diameter of the sample must be at least six times larger than the size of the largest particle.

The geotechnical engineer or engineering geologist should be aware that hand trimming samples, in situ freezing and coring, or impregnation of the material to be sampled is expensive. The additional costs must be considered before the investigation is begun. If the hand trimming method is selected, cribbing and shoring of the walls of the excavation may be needed. If in situ freezing is selected, the formation must be free draining and the field freezing procedures must be designed to ensure that the freezing front advances one dimensionally. The costs and logistics of the additional field support equipment should also be considered. If impregnation is used, coordination with the laboratory is mandatory to ensure that the impregnation material can be removed prior to laboratory testing.

d. Selection of sampling device. The data which are presented in Table 2-3 may be used as a preliminary guide for selecting a sampling apparatus and/or method for obtaining undisturbed samples of various materials. However, other factors, such as soil conditions, equipment availability, costs, and operator experience, may dictate the selection of an alternative sampling apparatus.

2-5. Borehole Layout, Depth and Interval of Sampling, and Sample Diameter

The borehole layout, sampling interval, and depth of samples are controlled to a major extent by the complexity of the geological conditions, the availability of equipment, and the type of project and its size. There are no hard and fast rules stating the number and depth of samples for a particular geotechnical investigation. Although considerable knowledge of the geological conditions may be available from the preliminary studies, including the review of the literature, maps, photographs, and the site reconnaissance, the site investigation is frequently a "learn as you go" operation. A guide for planning the boring program is suggested in the following paragraphs. The user is reminded, however, that each boring and sampling program must be planned and executed within monetary constraints with appropriate consideration given to other variables which may affect the site investigation.

Most geotechnical investigations fall into one of the following categories, or combination of categories, depending upon the size of the project:

a. Small isolated structures, such as houses. One borehole may be sufficient, especially if a number of small structures are placed relatively close together and the geology does not vary significantly over the site.

b. Compact projects, such as buildings and landslides. The borings may be relatively deep and closely spaced.

c. Extended projects such as highways, airport runways, electrical powerlines and pipelines, and reservoirs. Except for reservoirs, the borings may be relatively shallow and widely spaced. The spacing or frequency of the borings must be judged depending upon the site variability. For reservoirs, the depths of borings may be considerable to define the limits of impermeable soil.

Hvorslev (1949) suggested the following general considerations for planning the subsurface investigation:

> "The borings should be extended to strata of adequate bearing capacity and should penetrate all deposits which are unsuitable for foundation purposes - such as unconsolidated fill, peat, organic silt and very soft and compressible clay. The soft strata should be penetrated even when they are covered with a surface layer of high bearing capacity. When structures are to be founded on clay and other materials with adequate strength to support the structure but subject to consolidation by an increase in the load, the borings should penetrate the compressible strata or be extended to such a depth that the stress increase for still deeper strata is reduced to values so small that the corresponding consolidation of these strata will not materially influence the settlement of the proposed structure.
>
> Except in the case of very heavy loads or when seepage or other considerations are governing, the borings may be stopped when rock is encountered or after a short penetration into strata of exceptional bearing capacity and stiffness, provided it is known from explorations in the vicinity or the general stratigraphy of the area that these strata have adequate thickness or are underlain by still stronger formations. When these conditions are not fulfilled, some of the borings must be extended until it has been established that the strong strata have adequate thickness irrespective of the character of the underlaying material.
>
> When the structure is to be founded on rock, it must be verified that bedrock and not boulders have been encountered, and it is advisable to extend one or more borings from 10 to 20 ft into solid rock in order to determine the extent and character of the weathered zone of the rock.
>
> In regions where rock or strata of exceptional bearing capacity are found at relatively shallow depths - say from 100 to 150 ft - it is advisable to extend at least one of the borings to such strata, even when other considerations may indicate that a smaller depth would be sufficient. The additional information thereby obtained is valuable insurance against unexpected developments and against overlooking

> foundation methods and types which may be more economical than those first considered.
>
> The depth requirements should be reconsidered, when results of the first borings are available, and it is often possible to reduce the depth of subsequent borings or to confine detailed and special explorations to particular strata."

The primary exploratory borings should provide nearly continuous samples for classification and logging. However, sampling plans should be flexible to permit samples to be obtained for specific testing requirements or to answer questions regarding stratification changes, anomalies, etc. Although the boring plan and sampling interval is the responsibility of the geotechnical personnel, field conditions may demand that the inspector and the drill rig operator use judgment and modify the investigation to obtain complete and comprehensive information on the site conditions. Changes to the program, i.e., depth of borings, number of borings, and spacing of boreholes, may be required, depending upon the subsurface conditions which are encountered.

Table 2-4 is presented as a preliminary guide for geotechnical personnel for planning the boring and sampling program. This program is not intended to be a rigid requirement for Corps' geotechnical site investigations. It is suggested merely as guide for preliminary planning of the boring and sampling program. Although the data in this table suggests only undisturbed sampling operations, common sense directs that some general sample (disturbed) borings are needed to guide the planning for the more expensive undisturbed sampling locations, depths, and sampling intervals. The final boring program should be sufficiently flexible to permit geotechnical personnel to obtain a comprehensive understanding of the site, including anomalies or other features, while operating within budget and time constraints.

Table 2-5 provides the project engineer with guidance for selecting the appropriate diameter of sample or core which is compatible with the desired laboratory tests on undisturbed specimens or the required weight of material for tests on reconstituted soil specimens. A small specimen should be taken from the bottom of each undisturbed sample. This material may be used for classification and water content determinations. Although the small specimen may not represent the entire sample, a descriptive log of the boring and these specimens provide a basis for assigning laboratory tests.

Table 2-1
Direct Observation of Subsurface Conditions (after U.S. Department of the Interior, Bureau of Reclamation 1974)

Method	Type of Excavation or Boring	Remarks
In Situ Examination	Test pits/trenches	Excavation can be dug by hand or machine. The depth is usually limited to the depth of the water table. Shoring and cribbing are required for depths greater than approximately 1.2 m (3.9 ft).
	Large bored shafts, tunnels, and drifts	The excavation is fairly expensive. There may be a smear zone due to augering. Limitations may include confined working space and difficulty of identifying discontinuities.
	Borehole cameras	Dry hole is necessary to permit the examination of joints.
Boring and Drilling Techniques	Hand augering	Light, portable method of sampling soft to stiff soils near the ground surface.
	Light percussion (Shell and auger)	In clays, steel tube is dropped; soil is wedged inside. In granular soils, water is placed in bottom of cased borehole. Shell is surged to loosen the soil which precipitates in a tube on top of the shell.
	Power auger drilling	Bucket or auger is connected to drill rods. Torque is transmitted to auger by the kelly. Flight augers (continuous- or short-flight) may be hollow- or solid-stem. Soils may be mixed and nonrepresentative. Heavy downward pressure disturbs soils in advance of the auger.
	Wash boring	Soil particles are eroded and moved to the surface by jetting water from a bit at the base of the drill string. The drill rod is continuously rotated and surged as the borehole is advanced. Soils may be mixed and nonrepresentative.
	Rotary core drilling	Combined action of downward force and rotary action. Most common equipment is a core barrel fitted with a cutting bit. Modifications to rotary core drilling method include open-drive samplers and piston samplers.

Table 2-2
Causes of Soil Disturbance

Before Sampling	During Sampling	After Sampling
Base heave	Failure to recover	Chemical changes
Piping	Mixing or segregation	Migration of moisture
Caving	Remolding	Changes of water content
Swelling	Stress relief	Stress relief
Stress relief	Displacement	Freezing
Displacement	Stones along cutting edge	Overheating
		Vibration
		Disturbance caused during extrusion
		Disturbance caused during transportation and handling
		Disturbance caused due to storage
		Disturbance caused during sample preparation

Table 2-3
Guide for Selecting Sampler for Obtaining High Quality Undisturbed Samples

Soil Type	Suggested Sampler Type or Method
Very soft cohesive soils Organic soils Varved clays	Stockinette sampler, foil sampler, or fixed-piston sampler
Soft-to-medium cohesive soils	Fixed-piston sampler
Fine-to-medium sands above the water table	Hand trimming using the cylinder with advanced trimming technique Fixed-piston sampler in a cased and/or mudded borehole
Fine-to-medium sands below the water table	In situ freezing and coring Fixed-piston sampler in a mudded borehole
Alternating layers of soil and rock Hard or dense cohesive soils Rock	Rotary core-barrel sampler

Table 2-4
Suggested Boring Program for Various Engineering Structures (after Dunlap 1980) (Continued)

Structure	Number of Borings/Spacing	Depth of Borings	Remarks	
Rigid frame structure	1 boring per 230 sq m[1] of ground floor area	1-1/2 times the minimum dimension of footing below the base of the footing Pile footings - 1-1/2 times the minimum dimension of an imaginary footing located at 2/3 of the expected depth of piles	Cohesive soils Cohesionless soils	- continuous undisturbed samples for the first 3 meters - intermittent samples at 1-1/2 to 3 m intervals thereafter - sample at every change of soil type - obtain undisturbed samples (if possible) or conduct in situ soundings such as SPT or CPT tests
Continuous truss (girder)-type bridge	Minimum of 1 boring at every pier/footing	1-1/2 times the minimum dimension of footing below the base of the footing Pile footings - 1-1/2 times the minimum dimension of an imaginary footing located at 2/3 of the expected depth of piles	Cohesive soils Cohesionless soils Competent rock	- pier size < 50 sq m - continuous undisturbed samples at each pier - pier size - 50 to 100 sq m - 2 continuous undisturbed samples at each pier - pier size - 100 to 250 sq m - 4 continuous undisturbed samples at each pier - pier size > 250 sq m - minimum of 5 continuous undisturbed samples at each pier - obtain undisturbed samples or soundings as for cohesive soils - trace formation at each pier - if in doubt of rock quality, drill at least 6 m into formation
Levees	Levee height = 3 to 6 m; space borings at 300 m intervals	Depth of boring - 6 m	Cohesive soils Cohesionless soils Locate borings along centerline of proposed structure	- continuous undisturbed samples - continuous undisturbed samples or soundings
	Levee height = 6 to 12 m; space borings at 230 m intervals	Depth at least equal to height of levee		
	Levee height = 12 to 18 m; space borings at 150 m intervals	Depth at least equal to height of levee		
Earth dams	See remarks column	Depth at least equal to height of dam or twice the maximum head, whichever is greater Trace the top of the impervious zone	Preliminary investigation Primary investigation Obtain in situ permeability and pore pressure measurements Cohesive soils Cohesionless soils	- maximum stress occurs approximately at midpoint of slope between the centerline and toe of proposed structure. Establish a square grid pattern of borings located upstream and downstream of dam centerline near midpoint of slope in a direction with respect to dam centerline - trace the limits of various strata, e.g., sand - treat power plants, spillways, and other control structures as rigid frame structures - obtain adequate subsurface data to define the character of the abutments - continuous undisturbed samples - continuous undisturbed samples or soundings
Borrow pits	Use a 60-m grid spacing	Maximum depth to water table or working depth of equipment	Disturbed samples are satisfactory; may use augers to obtain samples	

[1] 1 m = 3.28 ft; 1 m^2 = 10.76 ft^2

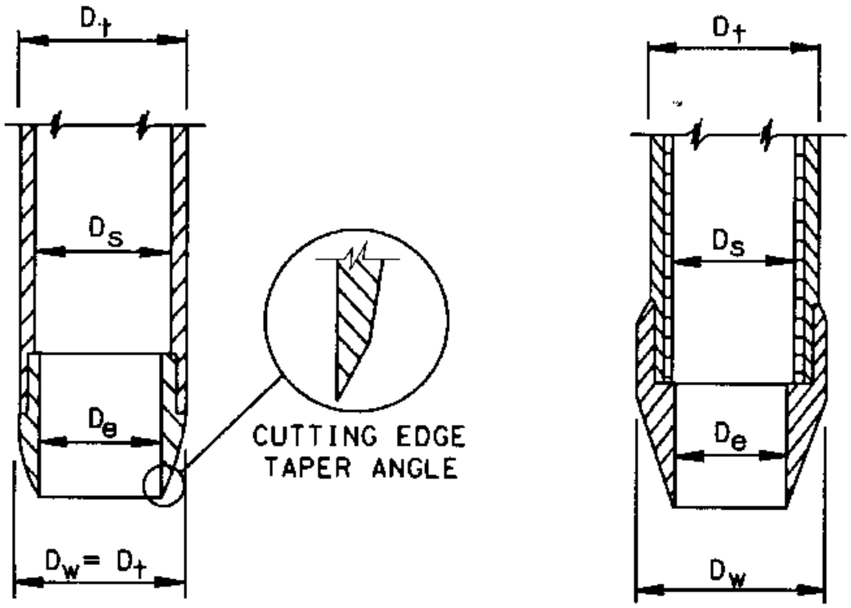
Table 2-4
(Concluded)

Structure	Number of Borings/Spacing	Depth of Borings	Remarks
Roads	For 2 lane highways: 1 boring per 150 m along centerline and at each major change of soil profile For multilane highways: 1 boring per 75 m along centerline; borings may be staggered	For excavations and level terrain: 3 m below level finished grade For compacted embankments: treat as for levees For rock: extend 0.75 m into rock	Cohesive soils - continuous undisturbed samples Cohesionless soils - continuous undisturbed samples or soundings
Airfields	See remarks column	See remarks column	Preliminary investigation - place borings at 300 m intervals in square grid patterns to a depth of 6 m. Samples may be disturbed. Site facilities based upon preliminary investigation. Primary investigation - Runways - site two lines of borings in a square grid pattern at 30 m on either side of runway centerline to a depth of 6 m or 1.5 m into rock - Taxiway - place borings at 60 to 76 m intervals along centerline to a depth of 6 m - Apron - place borings in a 60 to 75 m square grid pattern to a depth of 6 m
Houses	1 boring per 8000 sq m in new subdivision 1 boring per individual lot	To unweathered rock or to 4.5 m, whichever is lesser	Obtain samples at 1.5 m intervals using undisturbed sampling techniques for cohesive soils or undisturbed or sounding techniques for cohesionless soils

Table 2-5
Minimum Sample Diameter or Dry Weight for Selected Laboratory Tests

		Minimum Sample Diameter[1]		Minimum Dry Weight[1]	
Sample Type	Test	cm	in.	kg	lb
Undisturbed	Unit weight	7.6	3.0	----	----
	Permeability	7.6	3.0	----	----
	Consolidation	12.7	5.0	----	----
	Triaxial compression	12.7	5.0[2]	----	----
	Unconfined compression	7.6	3.0	----	----
	Direct shear	12.7	5.0	----	----
Disturbed	Water content	----	---	0.2	0.5
	Atterberg limits	----	---	0.2	0.5
	Shrinkage limits	----	---	0.2	0.5
	Specific gravity	----	---	0.1	0.2
	Grain-size analysis	----	---	0.2	0.5
Reconstituted	Standard compaction	----	---	13.5	30.0
	Permeability	----	---	0.9	2.0
	10.2-cm-diam consolidation	----	---	0.9	2.0
	Direct shear	----	---	0.9	2.0
	3.6-cm-diam triaxial (4 points)	----	---	0.9	2.0
	7.2-cm-diam triaxial (4 points)	----	---	4.5	10.0
	15-, 30-, or 38-cm-diam triaxial (4 points)	----	---	Coordinate with laboratory	
	Vibrated density	----	---	Coordinate with laboratory	

[1] All particles pass the U.S. Standard Sieve No 4 (3.8 mm)
[2] Triaxial test specimens are prepared by cutting a short section of a 12.7- cm- (5-in.-) diam sample axially into four quadrants and trimming each quadrant to the proper size. The material from three quadrants can be used for three tests representing the same depth. The material from the fourth quadrant is usually preserved for a check test.



INSIDE CLEARANCE $\quad C_i = \dfrac{D_s - D_e}{D_e}$ CONTROLS INSIDE FRICTION

OUTSIDE CLEARANCE $\quad C_o = \dfrac{D_w - D_t}{D_t}$ CONTROLS OUTSIDE FRICTION

AREA OR KERF RATIO $\quad C_a = \dfrac{D_w^2 - D_e^2}{D_e^2}$ $\dfrac{\text{VOLUME OF DISPLACED SOIL}}{\text{VOLUME OF SAMPLE}}$

Figure 2-1. Parameters which affect sample disturbance: a schematic of a sampling tube and cutting shoe (after Hvorslev 1949)